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Fuzzy Urban Traffic Signal Control – an Overview

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Abstract. In the last years, there have been many attempts made to improve urban traffic signal control systems as this is one of the most cost-effective ways to improve the traffic flow through a network of intersections. Besides the traditional methods for traffic signal control that are usually based on a traffic flow model, the development of new systems started to consider the various emerging technologies including artificial intelligence. Application of metaheuristic methods has proven to be worth of being researched. One of them is particularly fuzzy logic when combined with methods for system optimization. It offers a greater degree of flexibility, adaptability and above all the possibility of handling uncertain information and dealing with conflicting situations. We made an overview of the research that has been done so far in this area.

Key words: traffic signal control, fuzzy logic, hybrid systems, distributed control

Mehko upravljanje mestne prometne signalizacije – pregled

Povzetek. Izboljšanje sistemov za upravljanje mestne prometne signalizacije je eden cenovno najučinkovitejših načinov za izboljšanje prometnega pretoka skozi mrežo semaforiziranih križišč. Pri razvoju novih sistemov se zadnja leta poleg tradicionalnih metod, ki temeljijo na uporabi modelov prometnega pretoka, čedalje več uporabljajo nove tehnologije, ki vključujejo uporabo umetne inteligence. Raziskave so pokazale učinkovitost metahevrističnih metod. Posebno mehka logika, tudi v kombinaciji z optimizacijskimi metodami, ponuja fleksibilnost, prilagodljivost, upravljanje pri netočnih informacijah in v konfliktnih situacijah. Naredili smo pregled raziskav s tega področja.

Ključne besede: prometna signalizacija, mehka logika, hibridni sistemi, porazdeljeno upravljanje.

1 Introduction

Urban traffic signal control systems are systems that control and coordinate signals in a group of intersections in order to enable the vehicles to move fluently though the traffic network. The traffic signal control systems are developed to achieve maximum effectiveness, depending on the goals and the measures for the quality of service that we use. The objective of a traffic signal control system is safety, but the main goal is usually to achieve shorter delays and travel times [1, 2]. Some of the researches focus also on other aspects, such as public transport priority or greater mobility for pedestrians and cyclists [12]. We expect from an up-to-date traffic signal control system to operate in real time and to adapt to the dynamic traffic conditions.

Traffic signal control systems, like the one that are in use today, emerged in the sixties of the last century. We divide them in three generations. The first generation signal control systems use pre-stored timing plans that are developed offline using historical data. These plans are optimized for stationary traffic demands and we usually switch between them depending on the time of the day. They are still in use today, but they serve also as benchmarks in the development of new signal control systems.

The second generation of urban traffic control systems introduced the traffic-dependent signal timing plans that are switched or generated in real time. These systems came out in the seventies. They operate from a centralized computer and are characterized by a common cycle length. Systems like these are still mostly in use today, but they lose effectiveness in situations of big and quick variations. The problems arise when new timing plans are implemented too frequently and the coordination is lost because of the oscillations between timing plans.

In the third generation we deal with adaptive traf-

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fic signal control systems that are able to adapt to traffic conditions, coping with complex flow patterns and unpredictable variations. They seek continuous optimal system performance. SCOOT [14] and SCATS [15] are two of the most known adaptive traffic signal control systems. They gather the data on traffic flows in real-time at each intersection. This data is fed via the traffic control signal box to a central computer. The computer makes incremental adjustments to traffic light timings based on changes in the traffic flow at each intersection. SCATS performs a vehicle count at each stop line, while SCOOT uses a set of advance vehicle detectors upstream of the stop line. This gives the system a higher resolution picture of the traffic flows and a count of the number of vehicles in each queue, several seconds before they touch the stop line. Other systems like RHODES [10] and OPAC [4] use distributed control instead of centralized control. They run locally and provide coordination between the intersections by talking to their neighbours. For example, an upstream intersection releases a queue of traffic and tells the downstream intersection when and how many vehicles to expect. This scheme allows to have different cycle lengths at signalized intersections, yet provides for signal coordination.

Research in the field of area traffic signal control by means of methods of artificial intelligence started in the 1990's, although the first paper about isolated traffic signal control with fuzzy logic was published already in 1977. The first applications used only fuzzy logic, then neural nets or genetic algorithms, afterwards these methods started to be used together in the so called hybrid systems. Fuzzy logic serves as a tool for knowledge representation and the description for the control logic. By using methods like neural nets or genetic algorithms we enable the fuzzy logic systems to adapt to the traffic patterns and to learn better signal control strategies. In this paper we will make a review of the research that has been done so far and we will describe different approaches that have been used. We are also experimenting in this field [8]. Systems like these are still evolving and only starting to be implemented in real environments. Examples are a fuzzy traffic signal control system for an isolated intersection in Finland [12] and a fuzzy ramp-metering system in Germany [1].

2 Fuzzy logic systems

Fuzzy logic is a control method suitable for managing conflicting goals with information given in linguistic terms. Representing the input information with fuzzy sets enables the system to handle uncertain information and inexact data.

Fuzzy logic maps the inputs values of the system to the output values. The system domain is divided in fuzzy sets that represent some linguistic values. For example the *traffic flow* can be *low*, *medium* or *high*. We define these linguistic values by membership functions that tell us to which degree is a given numerical value part of a fuzzy set. To some degree it can be part of more than one fuzzy set. We can do the same with the output space. The translation of numerical values to linguistic values is called fuzzyfication, while the opposite procedure is defuzzyfication (Fig. 1). The fuzzy inference describes and defines the system logic by using simple if-then rules.

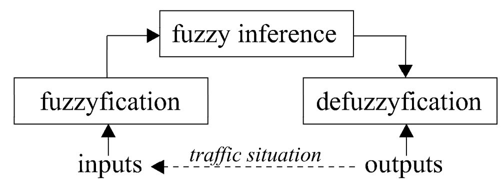

Figure 1. Structure of a fuzzy logic system

Rule example:
If the *demand* is *high*, then *extend* the *current phase*.

For a given input data also more than one rule can be combined and applied in order to obtain the desired control effect. Description of the system with fuzzy logic is very comprehensive and all the available knowledge can be easily integrated into the system.

The structure of a fuzzy logic system gives us the possibility to easily identify how and also why the system is operating the way it is. Hence, we can quickly see what is not good and where the problems we should be more focused on are. Modifying a fuzzy logic system is not difficult. The system is quite flexible: we can modify the membership functions that define the linguistic values, change their number, distribution, overlapping, modify, add or delete rules, change the system operators, apply different defuzzyfication methods and so on. But the hard part of the optimization procedure, especially of traffic signal control, is knowing if the system has improved or not, since there are no standard evaluation methods or measures of effectiveness. Another problem of a fuzzy logic system is that by increasing the number of linguistic variables and values, the rule base grows exponentially (when wanting to cover all the possible value combinations) which causes a combinatorial explosion. Usually, the solution to this is choosing a different system structure, hierarchical for example [3], or a distributed problem-solving approach. Instead of centrally we can operate locally at each intersection [2].

3 Hybrid systems

The construction optimization a fuzzy logic system can be a very time-consuming procedure. To solve this problem, many optimization techniques have been adopted in the area of fuzzy logic. The most widely used are neural nets and genetic algorithms [5]. The systems that combine these technologies are called neuro-fuzzy, genetic-fuzzy or simply hybrid systems. The optimization algorithms are also called learning algorithms. There are different types of learning procedures: offline or online, supervised, unsupervised or reinforcement type [5].

Neuro-fuzzy systems are represented as a feedforward neural network, where the units of the fuzzy logic system take the role of neurons. The connections between neurons follow the structure of the fuzzy system (Fig. 2). During the learning procedure the parameters of the neuro-fuzzy system are being updated in order to achieve the desired or the optimal behaviour. A standard learning algorithm is the backpropagation algorithm, common in supervised learning in neural networks, where the output of the network at each input is compared with a desired output, known in advance.

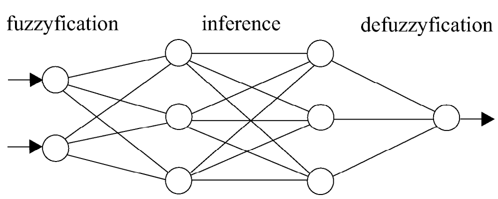

Figure 2. Example of a neuro-fuzzy structure

Genetic-fuzzy systems are another metaheuristic algorithm that join fuzzy logic with an optimization technique. Genetic algorithms are a search technique and are a particular class of evolutionary algorithms that use methods such as inheritance, mutation, natural selection, and crossover. First, we need to choose an adequate set of the system parameters that we want to modify and a suitable representation for the candidate solutions (Fig. 3).

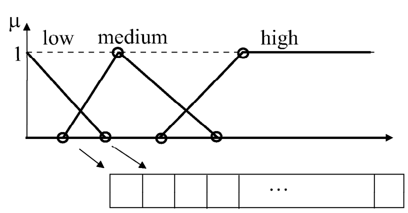

Figure 3. Example of a genetic-fuzzy representation

Traditionally, a solution can be represented by a string of bits, number or characters called chromosomes. Second, there must be some method of measuring the quality of any proposed solution, using a fitness function [3, 9].

There are many tools that offer offline optimization of the traffic signal timing parameters like Transyt or Syncro. They operate with historical and usually stationary data. Optimizing a fuzzy logic system offline would be similar. A bigger challenge is a learning procedure that optimizes the system online and consequently adapts the fuzzy traffic signal control system to the dynamically changing traffic domain.

Characteristic for the area of traffic signal control is that the outputs of the system are not predefined and neither are we interested in an exact output. The control actions have an impact on the traffic flow, delays and the number of stops and this is what we are concerned about. Thus, the learning algorithm must be goal-oriented and the learned signal timing strategies must be evaluated accordingly.

Two of the strategies for system evaluation are:

1. The traffic signal control system is connected with a traffic flow model predicting the system behaviour and estimating the system performance.

2. Instead of the traffic flow model, the control system uses the feedback from the traffic system to estimate the system performance. In this case the system can iteratively learn directly from the consequents of its own actions. This is what we call reinforcement learning.

4 Fuzzy traffic signal control

In this section we will present some of the approaches that were taken for fuzzy urban traffic signal control.

The first attempt to control traffic signals with fuzzy logic at isolated intersections was made by Pappis and Mamdany in 1977 [13]. They were followed by many others. One of the recent research projects was FUSICO conducted in Finland [12].

One of the first attempts to control traffic signals for a group of intersections with fuzzy logic was presented by Chiu and Chand in 1993 [2]. Their approach is based on a distributed system of cooperative local controllers. Each local controller uses a set of fuzzy decision rules to adjust the standard signal timing parameters: cycle time, phase split, and offset. The rules for adjusting the cycle time and phase split follow the general principles used by SCATS, except that cycle time and phase split adjustments are here coupled, determined with common rules. For example:

If *east-west saturation* is *low* **and**
north-south saturation is *high*
then *cycle time change* is *zero* **and**
east-west phase change is *negative medium.*

Their approach also allows the local controllers to have different cycle times when coordination is not so important. A group of rules limits the cycle time difference. They performed simple simulations to verify the effectiveness of the control scheme considering a mesh of nine intersections.

Mikami and Kakazu [9] are known for having used reinforcement learning and genetic algorithms, although they did not use fuzzy logic. With their multi-agent vehicle-actuated traffic signal control approach each signal controller learned its control plans individually by reinforcement learning. The long-term cooperation was acquired through the combinatorial search by genetic algorithms, but the learning scheme converged only when the environment was stationary.

Lee and Lee-Kwang [7] presented a distributed vehicle-actuated system for area traffic signal control that uses fuzzy logic. Each local controller of an intersection controls its own traffic and cooperates with its neighbors. The controllers consist of three modules (Fig. 4) that decide every 2 seconds about the next phase and whether to switch the green phase or not. The decisions are based on the information obtained from local and neighbour detectors. The system has 8 input, 1 output and 3 intermediate variables. It differs from other systems as it uses also the number of vehicles between this and the next intersection and the time that is still needed for the vehicles from the upstream intersection to get to this intersection. So this system needs two detectors per lane for every intersection. Three modules together have 61 rules. But the system doesn't consider pedestrians and it doesn't change or improve in time.

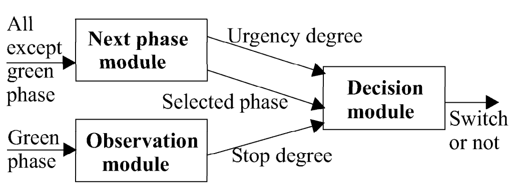

Figure 4. Fuzzy system with three ruleblocks

A similar approach was suggested also by Kosonen in [6]. He proposed traffic signal control that communicates with an on-line traffic simulation system that operates with real-time data. At the Helsinki University of technology they have been researching in the area of isolated fuzzy signal control [12] and they now try to use the experiences to run distributed control for an area.

We mentioned that fuzzy logic is being used also for ramp metering, which is a similar type of signal control, but it is used for managing traffic on freeways. There are various inputs like occupancy, speed, and the output variable is the metering rate. The ramp metering can be isolated or we can have more controllers for a freeway section that are coordinated. Bogenberger presented a coordinated fuzzy ramp metering control for a freeway section in Munich, Germany [1]. He proposed five different models, two of them are neuro-fuzzy and the others use genetic-fuzzy technology. Four models use for the evaluation a macroscopic traffic model that is called from an offline learning algorithm. The optimizing learning algorithm can be executed daily or every 15 minutes, depending on the model. On the other hand, one of the models, that have also been implemented in the field, called genetic reality, uses an online learning technique and it doesn't use a macroscopic traffic model. Instead, to achieve the system objective, which is the minimum total travel time, it uses feedback information. During the optimization, the membership functions are being updated, while the ruleblock remains unchanged.

Another type of distributed fuzzy traffic signal control was presented by Nakamiti and Freitas [11]. The system consists of a group of Local Problem Solvers and a Case-Based Mechanism (Fig. 5). Local Problem Solvers operate at individual intersections, they collect the input data at the given intersections and also from their neighbours. The input variables are traffic flows, waiting times and queue lengths and the system decides about the termination or the extension of the current green phase and informs the neighbours. The local controllers cooperate with regard to past experience that is organized in a case-base.

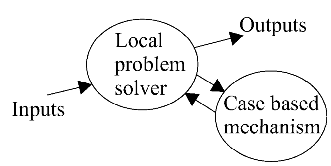

Figure 5. Connection with a case-based mechanism

An evolutive fuzzy case-based mechanism helps the Local Problem Solvers in unexpected situations to find an appropriate solution. Its main tasks are to identify and to retrieve similar cases, combine the selected cases, generate decision, and manage the case-base. Similar situations are retrieved and combined through genetic algorithms. After observing and analyzing the system performance by verifying the resulting delays and queues, the new case and its result are included into the case base, allowing better decisions over time.

Choy et al. [3] chose a different approach and used a model for traffic signal control with a hierarchical multi-agent architecture to provide different levels of control for the traffic network (Fig. 6). The architecture consists of three layers. The first layer consists of agents that control individual intersections. The agents in the second layer are zone controllers, while the third layer consists of one or more regional controller agents. The agents make decisions autonomously, they decide the policies (signal timing adjustments and direction of offset coordination) and the levels of cooperation. The policies are stored in a policy repository which performs arbitration and conflict resolution for the entire set of the recommended policies.

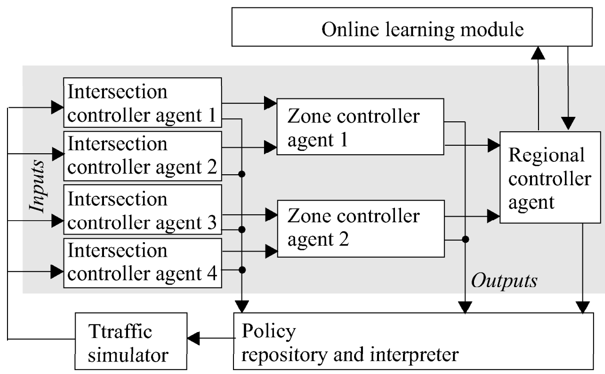

Figure 6. Hierarchical architecture of a fuzzy traffic signal control system

The system uses input variables like the traffic flow, rate of change of flow and occupancy. A special input for higher level agents is the cooperative factor that is the output of lower agents. Besides this, the system includes also an online reinforcement learning module for system optimization based on feedbacks from the environment. The role of this module is to generate reinforcements which are to be backpropagated to the agents to facilitate the dynamic adjustment of their parameters. The Choy's system uses fuzzy logic, neural nets, genetic algorithm and reinforcement learning all together. The signal policies are updated at the end of the signal phases.

The research in this area is still active, although the publications are very few. This is most probably due to an elevate commercial potential and business interests.

5 Comparison

The mentioned traffic signal control systems differ one from another in many aspects. Some control the green signal extensions [6, 7, 11] and others the standard control parameters such as the cycle, split and offset [2, 3] (Table 1). This affects the frequency at which the control actions must be computed. It is continuous versus point-wise, where continuous means decisions in regular intervals (usually seconds) while point-wise is at the beginning or end of a phase or cycle. Of course, the systems differ one from another already in terms of detector locations, input parameters, and of how they get the information from the intersections in the neighbourhood.

Our focus was on the traffic control systems using fuzzy logic. We thus distinguish between the systems that operate based only on fuzzy logic [2, 6, 7] and those that use also automatic optimization techniques [3, 11].

Table 1 shows some of the main characteristics of the traffic signal control systems we refer to in this paper. At this stage it is not known which of them gives better results as they have not yet been compared among themselves.

	object of control	level of control	position detectors	type of control
Scoot [14]	cycle, split, offset	central	upstream	based on traffic model
Scats [15]	cycle, split, offset	central	stop-bar	not model based
Rhodes [10]	phase durations	hierarchical	upstream	based on traffic model
Opac [4]	cycle, split, offset	distributed	upstream	based on traffic model
Chiu, Chand [2]	cycle, split, offset	distributed	stop-bar	fuzzy logic
Mikami, Kakazu [9]	phase extension	distributed	not specified	genetic reinforcement learning
Lee, Lee-Kwang [7]	phase extension	distributed	upstream, stop-bar	fuzzy logic
Nakamiti, Freitas [11]	phase extension	distributed	upstream	hybrid system
Kosonen [6]	phase extension	distributed	upstream	fuzzy logic
Choy et al. [3]	cycle, split, offset	hierarchical	stop-bar	hybrid system

Table 1. Studies in fuzzy traffic signal control

6 Simulations

The traffic signal control systems under development need to be tested and compared to other approved existing systems. There are many microsimulation tools on the market that are able to simulate the traffic at a very high level of detail. In order to evaluate a new traffic signal control system, the simulation program must provide interactions with an external signal control system. The simulation program creates traffic, propagates it through the traffic network in the simulation environment and generates detector inputs for the signal control system. The signal control system reacts to the detector inputs, computes the control actions and sends the traffic signals back to the simulator. The simulated vehicles react to these signals and according to them there are several measures of the signal control effectiveness computed. By simulating the same traffic conditions, different signal control systems can be objectively compared.

The mentioned studies include also simulations of their traffic signal controllers, but it should be noted that the different control procedures were simulated in different environments, traffic network configurations, traffic demands, etc. The control systems were usually compared with fixed time control, but not with other sophisticated methods. So we don't have an objective evaluation of the described signal control procedures. Two of the mentioned papers [1, 3] include simulations with real, dynamic traffic demand in real environments, and comparisons with state-of-the-art traffic signal control systems. Choy simulated a traffic network of a section of the central business district area of Singapore with 25 intersections controlled by his multiagent approach. The signal settings used for benchmarking were the actual signal plans implemented by GLIDE, the local name for SCATS. Detectors were placed at stop lines similarly to real-world installations. The resulting average delay per vehicle and the total stoppage time for vehicles showed an improvement of 15% and 30%, respectively, during the morning peak hour, and even 40% and 50%, respectively, after all the 6h simulation runs. These are but few simulations, but they nevertheless show us that there is a big potential in improving the traffic signal control systems.

7 Conclusion

The continuously growing traffic density and increasing demands for more efficient transport call for an improvement in the traffic signal control. We presented the past research in the area of traffic signal control that proposed the use of fuzzy logic and various optimization techniques that adopt genetic algorithms or neural nets. Their results show a great potential in making the traffic signal control systems more flexible, transparent and adaptable to the traffic dynamics, while producing smaller delays. Consequently, to evaluate and compare different traffic control systems we need a unified measure for the quality of service and examples that would serve as benchmarks in the development of new systems. However, the research in this area is still active as computer science continues to offer new methods towards achievement of better solutions.

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